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AI Based Analysis and Design of on-Site Power Generation By Integrating Solar, Wind, Biomass And Battery For Rural and Urban Areas - Perspective Pakistan

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Abstract

The severe global climate changes due to emissions of carbon dioxide and other toxic flue gases from power plants have compelled the world of power engineering to disintegrate the central station power generation into on-site generation. Secondly Pakistan being a poor country cannot afford to spend 60 % of its GDP on importing fossil fuels. Some parts of Pakistan are hot and sunny throughout the year we call them zone-I whereas some parts are cold and cloudy most of the year, we call them zone-II. For zone-I, we propose solar and biomass with batteries. For zone-II we propose wind and biomass with batteries. The load is also connected with a local distributed generation source referred as source-I and own source of generation is referred as source-II.

As we know that the Renewable sources vary intermittently, hence, it is Momentous to interconnect these renewable energy sources as hybrid energy system. In this paper, a AC/DC smart grid is proposed for integration and control of different voltage-current characteristics, renewable energy sources, storage units, local loads, and grids both under grid connected and isolated modes.

The proposed intelligent control strategy manages three key functions: (i) forecasting power output from variable renewable sources, (ii) regulating primary energy sources, storage, and the utility grid, and (iii) prioritizing load scheduling. This article presents the results of simulation studies conducted to evaluate the strategy's performance within a microgrid architecture.

Keyword: Hybrid renewable energy system, solar and wind power system, biogas, microgrid, artificial intelligence, state of charge of battery.

1. Introduction

The days of traditional electrical power grids are going to end due to severe greenhouse emissions and other certain environmental impacts. In future the renewable source of energy will govern the power sector [1]. The renewable energy is considered as cheapest and free of harmful emissions. The renewable energy sources could also be reliable if planned well through different sources and with use of modern supervisory technology. The World Green Building Council (WGBC) has set its target to achieve zero emissions buildings, reduction of CO₂ by 84 gigatons and capping the global temperature increase at 2°C by the year 2050 [2].

Pakistan is a developing country and spends 60% of her foreign reserve in importing fossil fuels. The developed countries had switched from traditional way of power generation to small scale distributed generation and now switching toward green buildings [3]. Hence to cope with energy crisis, the country

must take concrete steps to start on-site generation through different renewable sources favorable according to climate and weather conditions.

Pakistan has two different climates summer zone and winter zone referred as zone-I and zone-II respectively. For zone-I we propose solar and biomass with batteries whereas for zone-II we propose wind power and biomass with batteries. To guarantee the power reliability and continuity, and to exploit net metering concept, the option of grid mode is there.

Most net-zero buildings rely on the utility grid for at least half of their power, balancing the scales by sending an equal amount back throughout the year. Those that generate a surplus are known as "energy-plus" buildings, while those that fall just short of total self-sufficiency are labeled "near-zero" or "ultra-low energy" homes

For zone-I, our primary source is solar energy. During the daytime, solar energy is used directly in series with charging batteries. If there is any technical or bad weather interruption, the intelligent control system changeover to second source (biomass) through an automatic transfer switch (ATS). The batteries are used to overcome the momentary interruption and in case if both sources are weak. In case if all the three sources, i.e. solar, biomass and batteries are weak to a certain defined threshold level, then the building is connected to source-I i.e. grid. During the daytime, when the building has surplus energy, electrical energy is also transferred to grid.

For zone-II, our primary source is wind energy. If there is any technical problem or no wind, the intelligent control system changeover to second source (biomass) through an automatic transfer switch (ATS). The batteries are used to overcome the momentary interruption. In case if all the three sources, i.e. solar, biomass and batteries are weak to a certain defined threshold level, then the building is connected to source-I i.e. grid. During high wind pressure, when the building has surplus energy, electrical energy is also transferred to grid. The proposed scheme is feasible both for residence and commercial buildings and it reduces the load on grid and energy crisis in the country. The schematic diagram of the proposed system is shown below in figure-1.

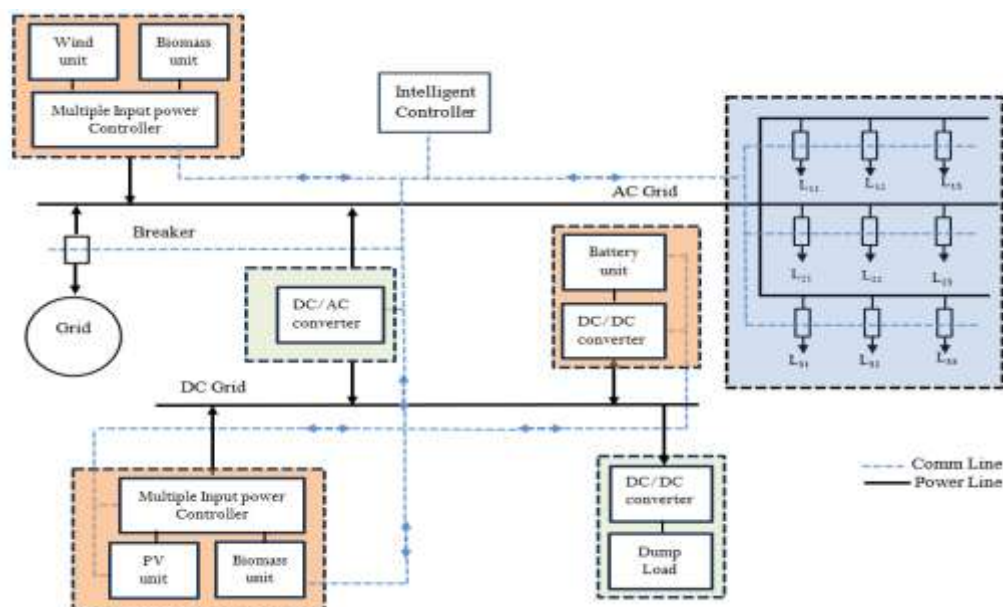


Fig-1 Schematic diagram of the proposed system

The only disadvantage of renewable sources is that they are not intermittent and depend on weather conditions [4]. Hence to cope with this problem, we have more than one source of energy and also connected with grid. We propose an intelligent control system to integrate and control the performance of different sources and switch over according to seek stability in power.

Developing a hybrid and efficient energy system is not an easy task. Our proposed scheme is a multitasking strategy which simultaneously predicts the output power being delivered by different renewable energy sources, control source-I and source-II, monitor the storage unit, schedule loads on priority and operate net metering. Our simulation results show that the performance analysis of the control strategy designed for the microgrid structure works efficiently and maintains good reliability.

The rest of the paper is organized as follows:

In section 2, we discuss the methodology and different power models. Results and simulation are discussed in section-3, and conclusion is given at section-4.

2. Methodology

2.1 Research design

This study espouses a simulation-based methodology to design and evaluate an intelligent hybrid AC/DC microgrid for renewable-energy-based electricity generation. The proposed microgrid integrates renewable energy sources, battery energy storage, local distributed generation, utility-grid support, power electronic converters, and controllable loads. The system is evaluated in different geographical zones in Pakistan under on-grid and off-grid operating conditions.

The methodology consists of four major stages:

- i. Classification of the selected area into renewable-energy zones.
- ii. Mathematical modelling of renewable sources, batteries, converters, loads, and grid interfaces.
- iii. Development of a forecasting and energy-management strategy.
- iv. Evaluation of technical, economic, environmental, and operational performance.

The proposed structure follows the general architecture of microgrid energy-management systems, in which forecasting is combined with generation scheduling and load management.

2.2 Geographical Operating Zones

Pakistan is divided into two representative renewable-energy zones according to the availability and variability of renewable resources.

Zone-I: Solar–biomass zone

Zone-I represents areas with high solar irradiance and relatively hot climatic conditions. The proposed generation mix for this zone consists of:

- Photovoltaic generation.
- Biomass-based generation.
- Battery energy storage.
- Local distributed generation, designated as Source-I.
- The proposed renewable-based generation system, designated as Source-II.
- Local AC and DC loads.

The PV system supplies power during periods of adequate solar radiation, while the biomass generator provides dispatchable power when solar generation is insufficient. The battery absorbs surplus renewable power and supplies the load during periods of generation shortage.

Zone-II: Wind–biomass zone

Zone-II represents areas with relatively cold or cloudy conditions and suitable wind resources. The proposed generation mix consists of:

- Wind-energy conversion system.
- Biomass-based generation.
- Battery energy storage.
- Source-I, representing the utility-grid connection.
- Source-II, representing the proposed generation system.
- AC and DC loads.

The wind turbine provides variable renewable power, whereas the biomass generator acts as a controllable backup source. Battery storage is used to compensate for short-term variations in wind power and to improve the reliability of the microgrid.

The separation into the two zones is intended to enable comparative assessment of solar-dominated and wind-dominated hybrid systems. In practical implementation, resource data should be obtained from ground measurements or established solar, wind, and biomass resource databases. Pakistan's renewable-resource mapping initiatives include solar, wind, and biomass assessment activities and provide geospatial datasets for renewable-energy planning.

2.3 Microgrid architecture

The proposed system is modelled as a hybrid AC/DC microgrid. The DC sub-grid contains the PV array or rectified wind generation, battery storage, DC loads, and the DC side of the bidirectional interlinking converter. The AC sub-grid contains the biomass generator, utility grid, Source-I, AC loads, and the AC side of the interlinking converter.

The two sub-grids are connected through a bidirectional AC/DC converter. This arrangement reduces unnecessary conversion stages and enables coordinated power exchange between the AC and DC networks.

The converter transfers power from the AC bus to the DC bus when DC-side generation is lower than the DC load and transfers power in the opposite direction when surplus DC power is available [6].

2.4 Mathematical modelling

2.4.1 Solar power Model

Solar cells are the fundamental devices used to convert photons directly into electricity. By managing these cells in series (to increase voltage) and parallel (to increase current), they form larger modules and arrays [7]. A basic and simplified circuit model of a solar panel is shown below in Fig. 2

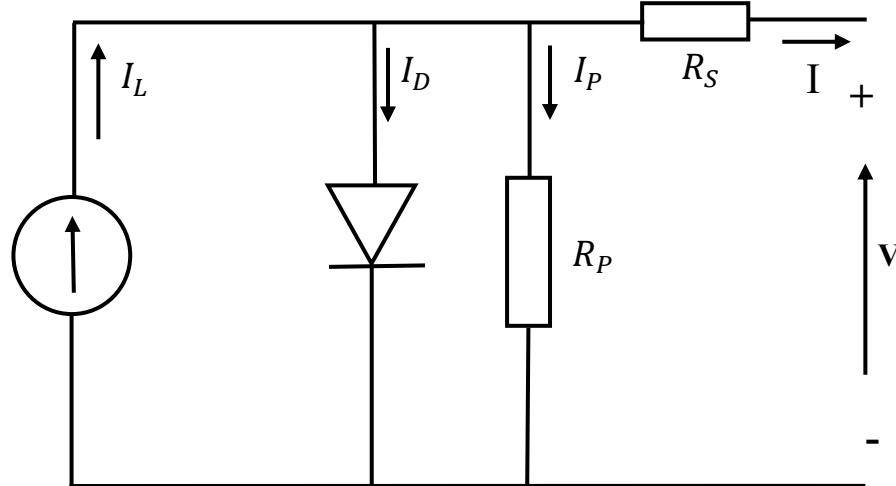


Fig. 2: Equivalent electrical circuit of PV panel module

$$I = I_L - I_D - I_P \quad (1)$$

Where I_L is photocurrent, I_D is diode current and I_P is shunt current. The diode current I_D is expressed by Shockley equation as:

$$I_D = I_o [e^{\delta(V+IR_S)} - 1] \quad (2)$$

Where I_o is reverse saturation current and shunt current I_P is defined as [8]

$$I_P = \frac{V+IR_S}{R_P} \quad (3)$$

Putting the value from eq (2) and (3) into eq (1), we get

$$I = I_L - I_o [e^{\delta(V+IR_S)} - 1] - \frac{V+IR_S}{R_P} \quad (4)$$

$$\delta = \frac{q}{\lambda k T_c}$$

Where q is electric charge, k is Boltzmann constant, T_c is the cell temperature and λ is shape factor and is given by

$$\lambda = \alpha + N_{SC} \quad (5)$$

α is ideality factor and N_{SC} is the number of cells in series in the module.

For sake of simplicity, the shunt resistance (R_P) is considered to be infinity. So, the last term in (4) is ignored. Hence, the single diode equivalent circuit model is given as [9]:

$$I = I_L - I_o [e^{\delta(V+IR_S)} - 1] \quad (6)$$

The output power from a PV module mainly depends on:

- The efficiency of your solar panels
- Your location
- The orientation of your solar panels

Power = Radiation $\times$ Area $\times$ efficiency

2.4.2 Measurement of biogas capacity and production

During last decade energy crisis in Pakistan has been forced the researchers to propose alternate solution to overcome the problem of power generation. On-site generation at low scale has been good idea to overcome this problem [10]. Interest in small-scale biogas technologies has increased in Pakistan. The main drives of this shift are the socio-economic and environmental benefits of biogas [11].

The volume of gas produced mainly depends on:

Digester volume, total feedstock volume, retention time of feedstock, elementary concentration of volatile solids, and local temperature.

The production of biogas can be calculated as [12]:

$$G = C \times V_d \times S \times \frac{k}{1+kR} \quad (7)$$

Where

G is the volume of the biogas produced (in m³ /day)

C is the biogas potential (in m³ /kg)

V_d is the volume of the digester (in m³)

S is the elementary concentration of volatile solids in the slurry (in kg/m³)

R is retention time of the feedstock (in days)

k is a constant showing the rate of gas production at a given temperature.

The output power is given by:

$$P = \eta_{Burner} \times v_f \times v_b \times CH_4 \quad (8)$$

Where

η_{Burner} is the Efficiency of the burner

v_f is the volume of fluid in digester

v_b is the volume of biogas produced per day

CH₄ is the methane proportionality

2.4.3 Wind Power

Wind turbine is an energy generating and converting mechanism to convert the kinetic energy of wind into mechanical energy and in turn into electrical energy [13].

The wind power mainly depends on:

Amount of air (volume), Speed of air (velocity) and Mass of air (Density).

The standard translational kinetic energy (K) of any object with mass (m) moving at a velocity (v) is given by [14]:

$$K = \frac{1}{2} m v^2 \quad (9)$$

Power in kinetic energy per unit time is given by

$$P = \frac{1}{2} m v^2 \quad (10)$$

The mass flow rate of the wind is given by

$$m = \frac{1}{2} \rho A v \quad (11)$$

Where

ρ is density of air (kg/m³), A is cross-sectional area of wind parcel (m²) and v is speed of wind (m/sec)

Evaluating eq (2) and (3), we get

$$P_w = \frac{1}{2} \rho A v^3 \quad (12)$$

According to Betz, we can convert about 60% of the kinetic energy present in the wind into mechanical energy using modern wind turbines [15]. Hence the maximum power (P_m) that we can exploit is the ratio of power extricated by the turbine to the total power contained in the wind, i.e. $P_m = \frac{P_T}{P_W}$

$$P_w = \frac{1}{2} \rho A v^3 P_m \quad (13)$$

2.4.4 Battery

Battery is an important unit of the system. The important parameter of this model should include charging and discharging characteristics, state of health (SOH) and state of charge (SOC) estimation, algorithm development, system optimization, and real-time simulation of battery management system design [16]. In our design, we consider 4.2-V 850 mAh Lithium-ion battery.

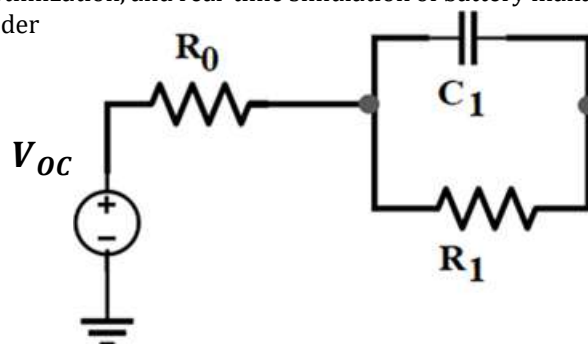


Fig.3 The Thevenin circuit model for the Lithium battery

Here we use the Thevenin equivalent circuit model to discuss the charging/discharging and other characteristics of the battery.

$$V_{oc} = R_o i_t + R_1 i_{rt} \quad (14)$$

$$i_t = i_{ct} + i_{rt} \quad (15)$$

$$i_{ct}/C_1 = R_1 \frac{di_{rt}}{dt} \quad (16)$$

Where V_{oc} is the open-circuit voltage of the battery, i_t is the current operating at V_{oc} with positive or negative sign depending on whether it is charging or discharging, respectively).

SoC of a battery is the level of available energy remaining, generally expressed as a percentage. SoC (i) maintains the uniformity of battery performance, (ii) protects the battery from over-charging and over-discharging (iii) Rationalize the utilization of energy, i.e. effectively use of limited energy. (iv) Forecast the remaining power. SoC is given as [17]

$$SoC = \frac{Q_c}{Q_N} = [Q_N - Q(I_n)]/Q_N \quad (17)$$

$$Q(I_n) = \int_{t_o}^t I_n dt \quad (18)$$

Where Q_c is the left-over capacity of the battery, Q_N is the built-in capacity of the battery, $Q(I_n)$ is the discharging current, and I_n is (t_o to t time) release power of the battery.

$$SoC = SoC_o - \frac{1}{Q_N} \int_{t_o}^t \eta I_n dt \quad (19)$$

Where Q_N is the build-in capacity, I is the current of the battery, and η is the charging-discharging efficiency.

2.5 Forecasting module

The first function of the intelligent controller is forecasting. Short-term forecasts are generated for [18]:

- Solar irradiance and PV output in Zone-I.
- Wind speed and wind-turbine output in Zone-II.
- Biomass-generator availability.
- AC and DC load demand.
- Battery state of charge.
- Utility-grid availability.

Historical weather and load data are divided into training, validation, and testing datasets. Forecast accuracy is evaluated using mean absolute error, root mean square error, and mean absolute percentage error:

$$MAE = \frac{1}{N} \sum_{i=1}^N |y_i - \hat{y}_i| \quad (20)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2} \quad (21)$$

$$MAPE = \frac{100}{N} \sum_{i=1}^N \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad (22)$$

where y_i is the measured value and $\hat{y}_i$ is the forecast value.

2.6 AI-Based Energy-Management Strategy

The AI-based energy-management system will determine the most appropriate operating action at each specific interval of time. The controller will receive information regarding [19]:

- Forecasted load demand.
- Forecasted solar and wind generation.
- Battery state of charge.
- Biomass availability.
- Grid status.
- Current operating condition of each component.

The dispatch priority may be defined as follows:

- Supply the load using available solar and wind power.
- Charge the battery using surplus renewable electricity.
- Use stored battery energy during renewable-energy deficits.

- Operate the biomass generator when renewable power and battery energy are insufficient.
- Import electricity from the grid when the system cannot satisfy demand.
- Export surplus electricity to the grid where net metering is available.

The controller may be formulated using reinforcement learning, fuzzy logic, or an AI-assisted rule-based method.

2.7 Converter and operating-mode control

The bidirectional AC/DC converter operates in different control modes depending on the condition of the microgrid [20].

In on-grid condition:

- The utility grid establishes the AC-side frequency and voltage.
- The converter regulates DC-bus voltage and controls active-power exchange.
- Reactive-power exchange is controlled according to the specified power factor or voltage-support requirement.
- Renewable sources operate at their available maximum power unless curtailed by the energy-management system.
- The battery absorbs surplus generation or supplies power during deficits.

In off-grid condition:

- The microgrid is electrically separated from the utility grid.
- A grid-forming source, battery inverter, biomass generator, or coordinated converter establishes AC voltage and frequency.
- The interlinking converter maintains the DC-bus voltage.
- Power balance is maintained through renewable generation, battery operation, biomass dispatch, and load prioritization.

A transition test is performed by opening and closing the utility-grid breaker to examine the stability of voltage, frequency, DC-bus voltage, and load supply during grid disconnection and reconnection.

2.8 Techno-Economic Evaluation

The economic performance of each optimized configuration will be evaluated using capital cost, replacement cost, fuel cost, operation and maintenance cost, grid electricity cost, and salvage value [21].

The net cost will be calculated as:

$$NC = C_{\text{cap}} + C_{\text{replace}} + C_{\text{O\&M}} + C_{\text{fuel}} + C_{\text{grid}} - C_{\text{salg}} \quad (23)$$

The levelized cost of electricity will be calculated as:

$$LCOE = \frac{\text{Annualized total system cost}}{\text{Annual electricity served}} \quad (24)$$

2.9 Environmental performance

The reduction in carbon emissions is estimated from avoided grid imports and reduced fossil-fuel consumption [22]:

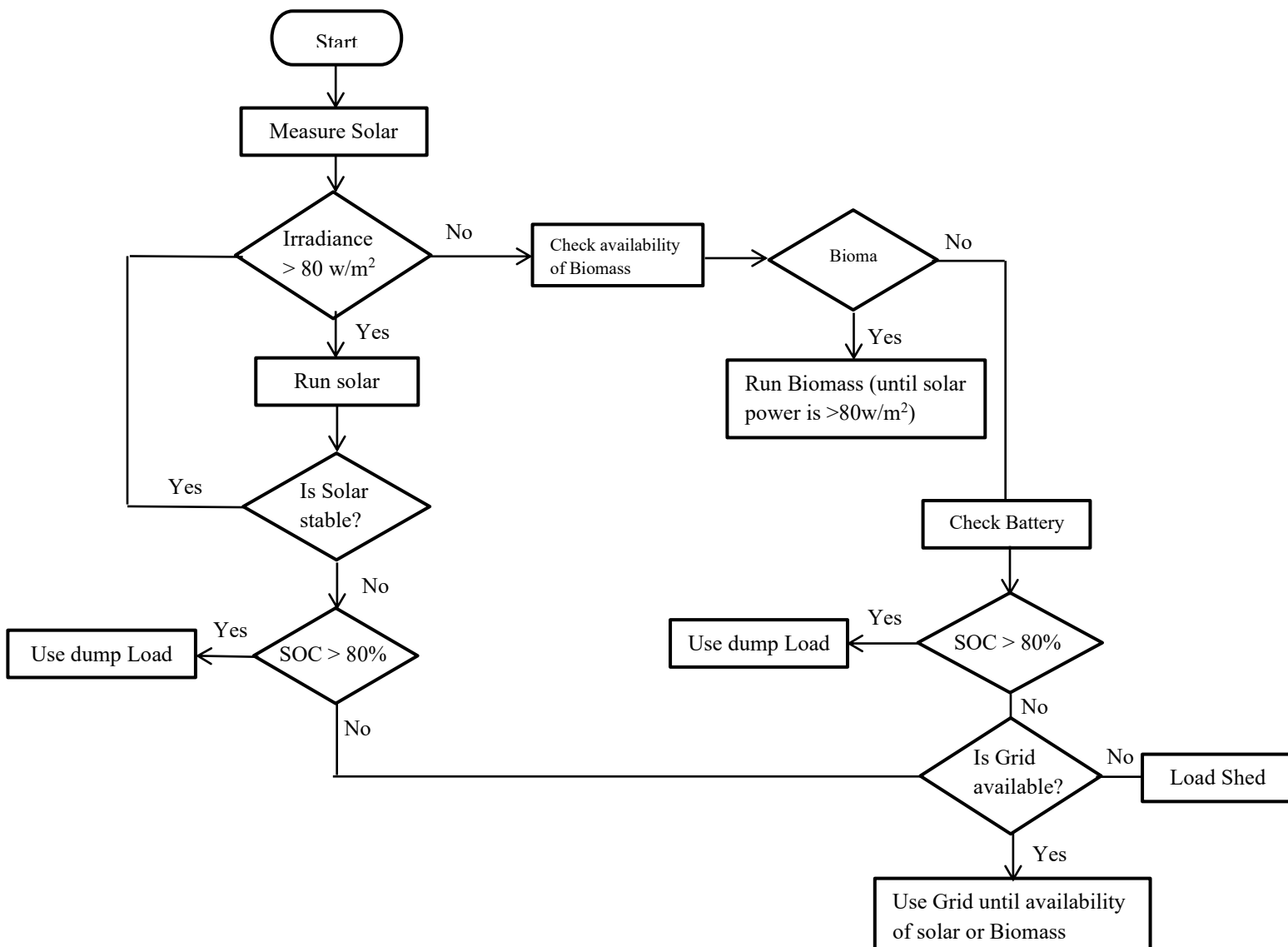
$$M_{\text{CO}_2} = \sum_{t=1}^T [EF_{\text{grid}} P_{\text{grid}}(t) + EF_{\text{fuel}} P_{\text{fuel}}(t)] \Delta t \quad (25)$$

where EF_{grid} and EF_{fuel} are the corresponding emission factors.

3 Results and Discussion

The flow chart-I illustrates the proposed scheme of zone-I which comprises of solar, biomass and batteries. Whereas flow chart-II illustrates the proposed scheme of zone-II which comprises of wind, biomass and batteries.

Flow chart-I



The training curves shown in fig-4 presents crucial insights into model performance during 1000 epochs of training on a regression task. Three key metrics, i.e. loss MSE (Mean Squared Error), MAE (Mean Absolute Error), and accuracy within a $\pm 5\%$ tolerance, are shown.

The MSE curves for training and validation initially drop steeply, indicating fast learning of data patterns. Both curves converge near zero with a small gap where validation loss remains slightly higher than training loss. The small difference indicates that this model can generalize without too much overfitting, and provides extremely accurate output. Just like the other MAE curves, the 50 000 MAE stops at a low value, and the difference between validation and training MAE is constant and small. This makes sense as the average error in prediction is very small. The closer than 5% metric, measuring the percentage of predictions near true values, has a more evident separation. Training accuracy jumps to roughly 84%, indicating robust training data fitting, while the validation accuracy levels off at around 65-70% and changes irregularly. It is a case of slight overfit, since the model has learned specific traits of the training data that do not reflect the general case. Generally, the model shows strong performance with small loss and MAE on both datasets, the gap in the accuracy indicates that the accuracy still has space to be increased. This can be done by using early stopping (training should come to a stop close to the maximum validation accuracy, approximate between epoch 500~600), weight regularization (L1/L2) or inserting drop out layer. This collection of plots is key for identifying learning pattern, determining how we will improve upon

what we see, and to identify how well the model will predict general unseen data as well as not falling into overfitting pitfalls. In energy load prediction with high priority source (solar, biomass, battery, grid), this analysis shall be used to generate trustworthy, generalizable, forecasts of actual observed loads.

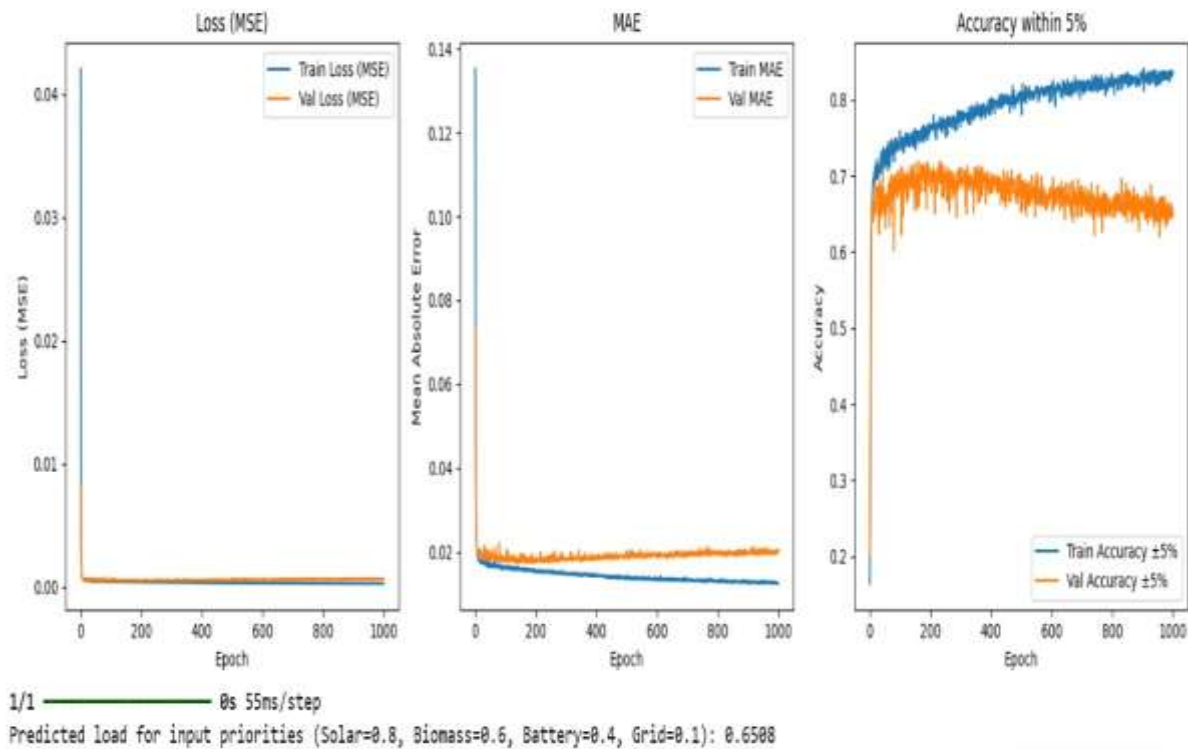


Fig-4 AI analysis of scheme-I

The load value that is predicted for the set of input priorities Solar= 0.8, Biomass= 0.6, Battery= 0.4, and Grid= 0.1 is 0.6508. This predicted load value is an estimation based on the trained neural network, which, given a set of source availability level indicators (0-1) can predict an overall load level. The inputs are all indicators of source priority/availability from highest (solar) to lowest (grid). As can be seen by the data that was used to train the neural network (Equation 1), the system has been trained to see how the load can vary depending on different source availability levels. When these input features are entered into the neural network model it can account for the non-linear relationships and interactions between the sources and assigns relative weights accordingly and a scalar output in the range between 0 and 1 (since the data used to train the network was normalized) is produced. In this case the predicted load value of 0.6508, in terms of the input source availabilities, is roughly 65% of the maximum power load of 1.

Flow chart-II

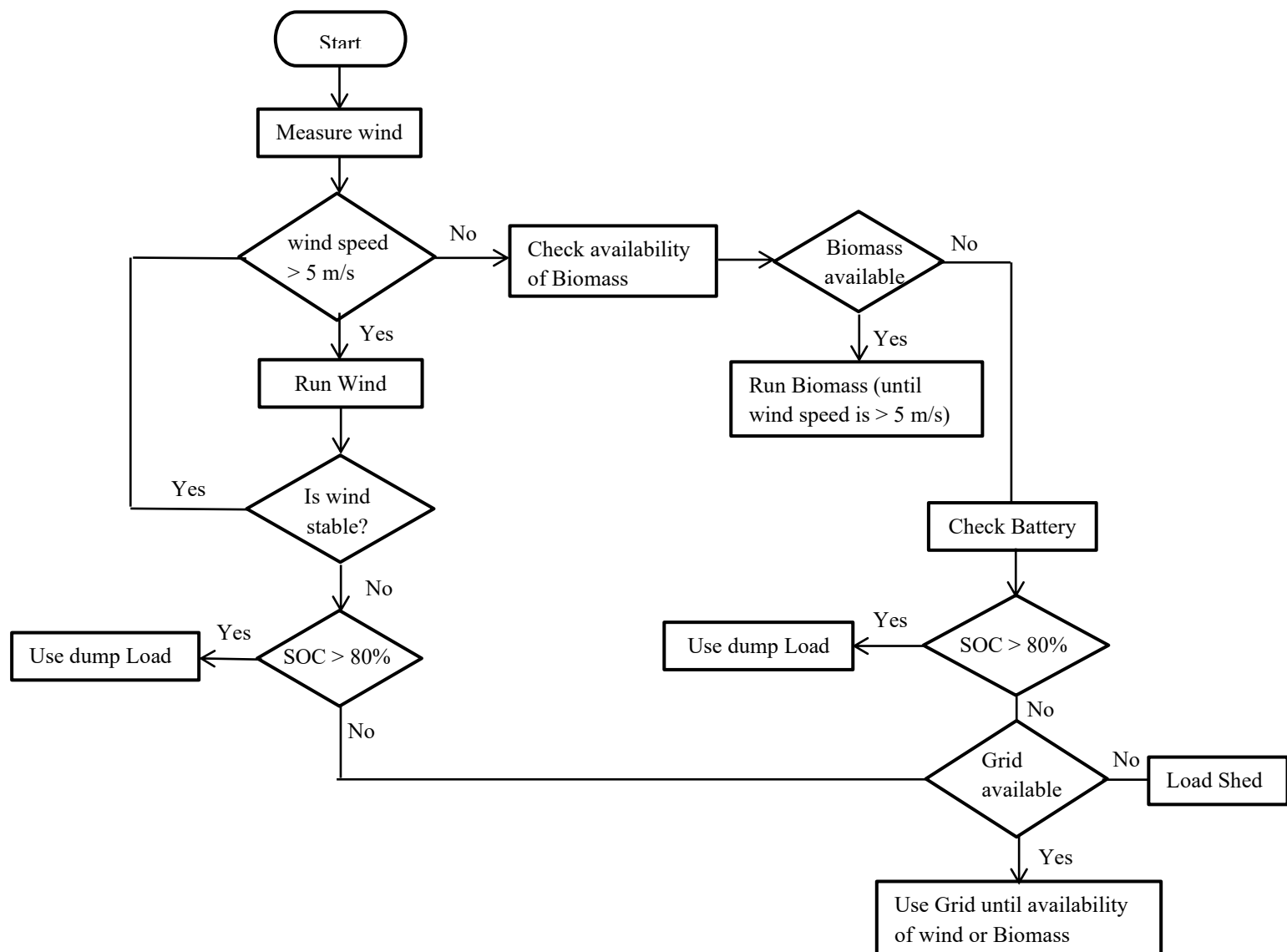


Fig-5 presents the integration of the two branches into a continuous way i.e. the machine learning model performance for load demand forecasting and the scheme of operation of the HRES. The overall presentation in this figure is a very informative display of the building blocks of smart grid operations. The two segments; a successful, generalized Machine Learning model for time-series prediction of demand for electrical load and the operational HRES scheme, are two pillars of the smart grid. The first half of the Figure -5 (towards the left) is presenting a well-done, highly successful generalized time-series prediction network for forecasting electricity load demand; this is very strongly evidenced by the three plots showing the history of the machine learning model training. The lines are showing the loss (MSE) and the mean error (MAE) and the three trends reported for all the training epochs totaling 1000. The convergence here is remarkably quick, shown by the precipitous drops of both MSE and MAE metrics within first 100 epochs and consistently close convergences between the training and validation lines, yielding extremely low end values (MSE 0.003 and MAE x 0.05), with a remarkably narrow gap being the most convincing indicator of a very successful generalization, machine learning model; the latter having very stable performance even on unseen data. The second half of the Figure-5, towards the right, again within the three columns, is indicating that the HRES operational scheme's scheme for managing power sources is employing a clear order of ranking to cater for the demand in terms of dispatchable (biomass) and stored (battery) renewable sources and the grid as the last resort. The operational scheme is relying on three-tier hierarchy order for wind speed.

The way the first tier works is; when the wind speed is > 5 m/sec, the turbines are switched to On (see Run wind) and they would be generating power from that point, the case is that when this is happening, the power production by the turbines in that case is likely to be 'over and above' what is needed, in this case, the power surplus would be managed by the Battery State of Charge (the SOC); if the SOC is above 80%, it would bypass the Battery management system and goes to 'Use Dump Load' i.e. stop charging the batteries and dump the power.

Moving to the second tier, when the wind speed is 5 m/sec, then the next source of power that needs to be managed is the availability of Biomass; the wind may or may not be available, but biomass is a dispatchable source of power (if there is some biomass) and power can be generated from that; in this case, the next step being to 'Run Biomass' till the wind speed is restored to above 5 m/sec, and then first tier is entered. Finally, when no wind (or not high enough wind to generate power) and no biomass available, the system now enters the third tier; from the existing state, the power now needs to be managed from Battery (if available for use or getting charged) or from the Grid; if the battery is available and if the storage level is above 80%, then again to 'Dump Load' (otherwise to the Battery system to charge), followed by when the 'Grid Is available' then the power is supplied from the Grid as a standby source to meet the load and recharge the batteries. The last resort being that when 'Grid is not available' as backup then there is nowhere left to go except 'Load Shedding'.

The detailed step by step management of Wind Biomass Battery/Grid using the sequential 'if else' logical operators as seen in the sixth column of the figure, is the equivalent of the way the energy management is happening in the background of a real world energy system; to managing 'dispatch-able' renewable power source (Biomass), its storage (Battery) and the external (grid) a sustainable, effective power management logic can be constructed using these high level industry standards and best practices. The game of demand forecasting with machine learning model and the 'demand management' with the energy systems flowsheet as seen in the figure, now together indicate that an integrated, sophisticated approach to smart energy management is in place. It can be safely concluded that based on the output of the machine learning based demand forecast, the energy management scheme is designed to successfully handle the 'dispatch-able' renewable (biomass) and the storage renewable (battery) energy sources rather than resorting to emergency 'load shedding'.

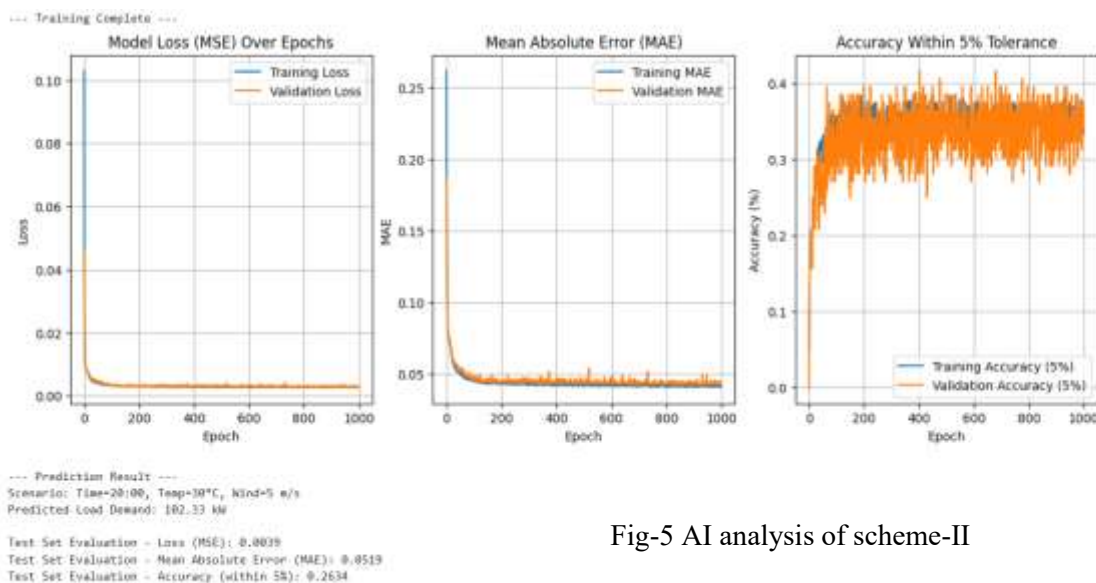


Fig-5 AI analysis of scheme-II

4. Conclusion:

This study demonstrates that an AI-enabled hybrid microgrid combining solar, wind, biomass, and battery storage can provide reliable, cost-effective on-site power for both rural and urban contexts in Pakistan, while reducing dependence on imported fossil fuels and lowering carbon emissions. By tailoring technology mixes to climatic zones—solar + biomass + batteries for hot, sunny Zone-I and wind + biomass + batteries for cold, cloudy Zone-II—the proposed architecture aligns resource availability with local demand profiles and improves system resilience against intermittency.

The intelligent control strategy, which integrates forecasting of renewable output, coordinated regulation of primary sources, storage, and the utility grid, and priority-based load scheduling, is shown through simulation to maintain stable AC/DC microgrid operation in both grid-connected and islanded modes.

Results indicate that such AI-driven energy management can increase renewable utilization, smooth supply-demand mismatches, and enhance power quality, thereby supporting 24-hour service with minimal load shedding in off-grid mode.

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